



# Applications of Wireless Technology in Space

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# Overview

- I. Introduction to wireless technology (RF, Acoustic, Optical)
  - Wireless standards – Capabilities and limitations
  - Reliability of wireless networks – Definitions and basic parameters
- II. Use case scenarios and environmental requirements
  - Space vehicles; Satellites and payloads; Surface explorations; Ground systems; Habitats
- III. Application specific requirements
  - Engine health monitoring; Wireless power transmission; Radio Frequency (RF) Communications; Cognitive networks; Environmental monitoring and sensors; Habitat systems; Sensors and actuators
- IV. Conclusions
  - Current interest areas; Potential technology areas for short and long term future implementations; technology road map.
- V. How to get started? Some examples...



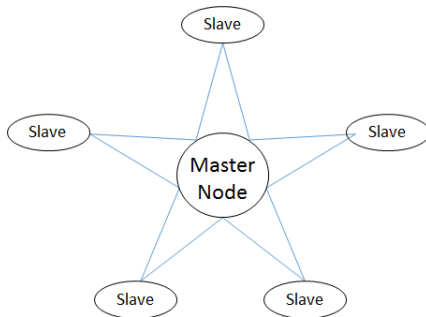
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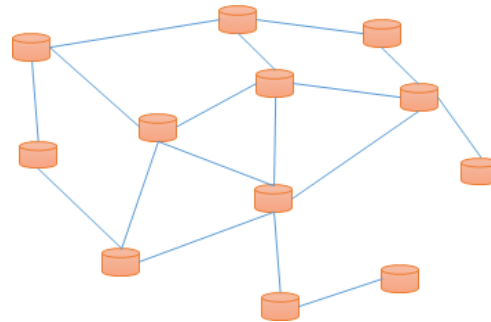


# Wireless standards — Capabilities and limitations

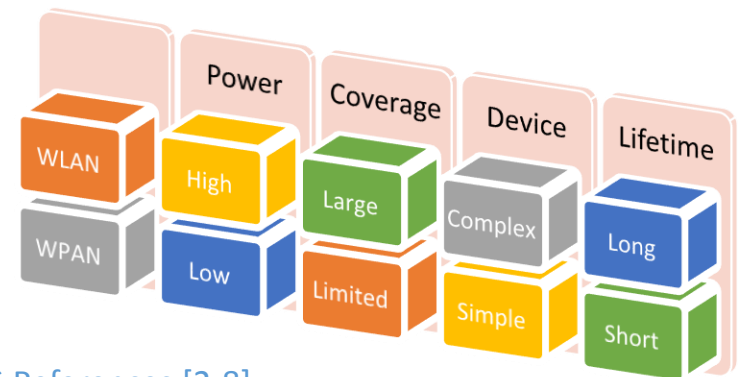
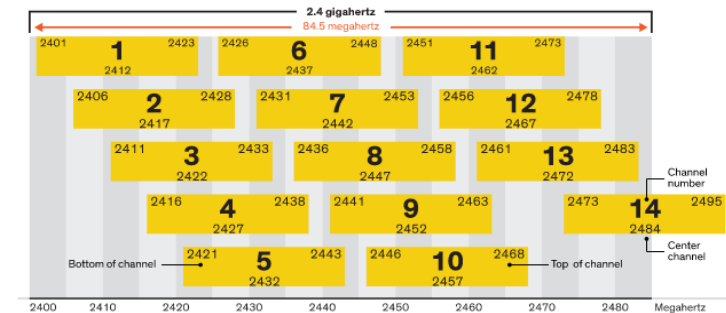
- WLAN: Wireless Local Area Network
- WPAN: Wireless Personal Area Network



Bluetooth: Master/Slave



ZigBee: Mesh

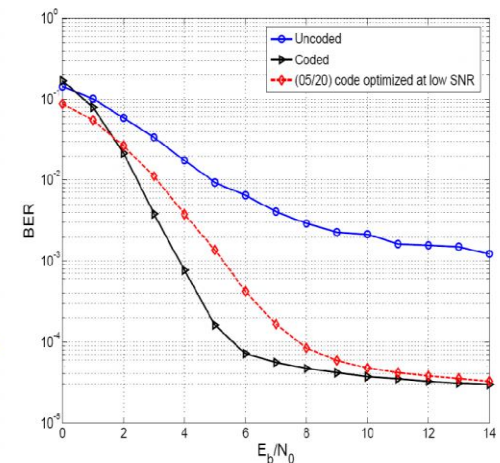
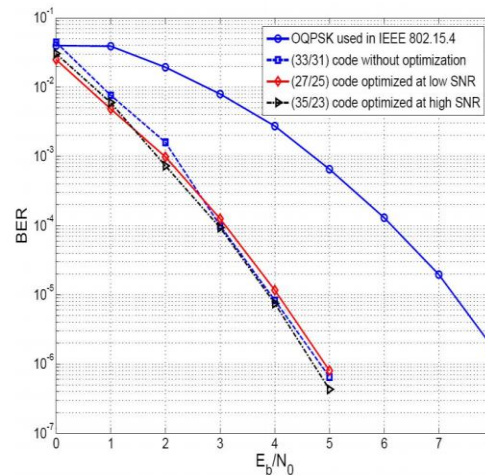
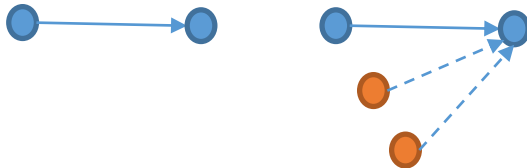
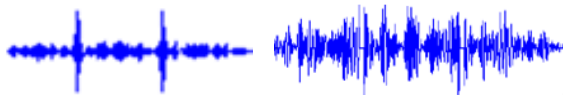


\* References [2-8]



# Reliability of Wireless Networks

- What is the definition of reliability?
  - End to end data throughput
  - Delay or latency
  - Bit Error Rate (BER) or Symbol Error Rate (SER) or Packet Error Rate (PER)
  - Packet loss or collision rate
- Example: QBSC'2007
  - AWGN (left)
  - Rayleigh fading (right)
- Example: Sensors'2013
  - One sensor (left), multiple (right)



\* References [9-10]



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# Space Vehicles

Space vehicles operate in extreme conditions with notable vibrations on their various sub-systems. Monitoring critical systems such as thermal and pressure systems, cryogenic fluid management, HVAC, ECLSS, Lighting Monitoring, Docking, and Rendezvous systems require specific considerations as follows\*. Most of these systems are hard to reach and not accessible easily. The wireless system design need to accommodate operations in confined spaces and often closed metallic chambers or sometimes even inside fluid environments at cryogenic temperatures. A recent work at MSFC demonstrated proof of concept for wireless sensing inside a fuel tank\*. Monitoring the engine and heat shield requires sensors that can operate in high temperature environments with harsh chemical vapors present.

## Challenges:

- Wide range of temperature variations
- Vibration tolerance
- Accessibility in confined environments
- Signal propagation in metallic enclosures

## Benefits:

- Acquiring more data from supporting structures and engine itself
- Reducing weight due to cable elimination
- Dynamic performance control with wireless sensing and actuation



SLS

\* References [11-12]



# Example: Test of WSN on board a Rocket



2009, 2011, and 2013 Mojave, CA



Funded by NASA  
MSGC and CSGC





# Satellites and payloads

Satellites and payloads operate in harsh environment and often require monitoring and protection against extreme temperature changes and radiation. Whether using radiation hardened hardware or adding internal heaters or coolers to keep the equipment in desirable environmental condition, it is necessary to monitor the internal temperatures and radiation doses at all times. Although, it may not make sense to replace a short few cm wire inside a small satellite with wireless, but for some applications were drilling a hole in the payload or satellite's exterior body may lead to loss of heat and energy, short range magnetic coupling wireless solutions will become important. Other applications include monitoring external solar arrays for MMOD impact or damage evaluation as well as transferring power between two disjoint sections.

## Challenges:

- Wide range of temperature and radiation variations
- Size and weight limitations
- Signal propagation in metallic enclosures
- Power constraints

## Benefits:

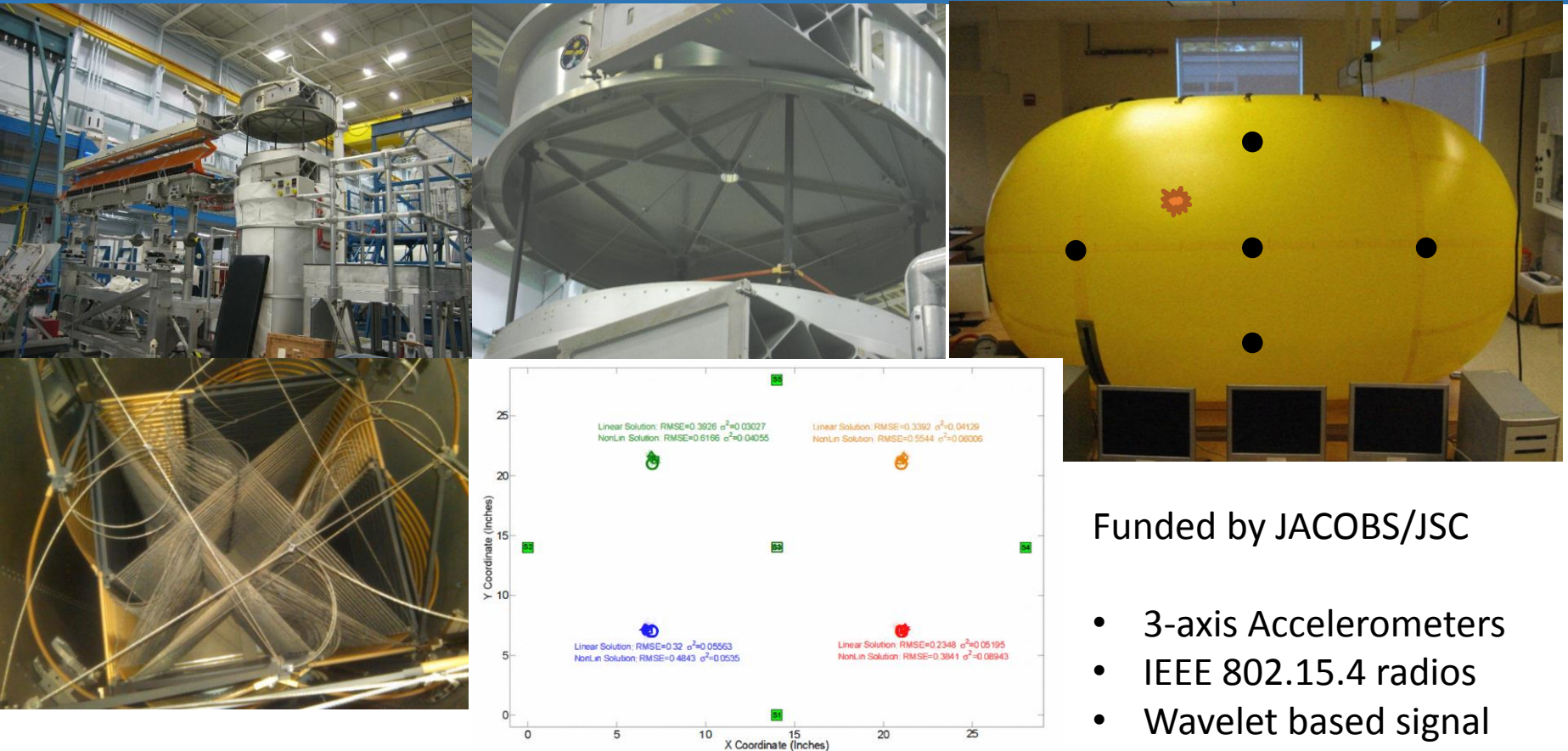
- Wireless connection between two disjoint sections
- Reducing heat loss by avoiding drilling holes
- More efficient use of harvested power



Cube Sat



# Example: ISS Solar Array Impact Localization



Funded by JACOBS/JSC

- 3-axis Accelerometers
- IEEE 802.15.4 radios
- Wavelet based signal processing



# Surface explorations

Autonomous exploration of planetary surfaces may require machine vision and robotics arms to recognize various object types and manipulate them, drill ground to collect soil samples, and navigate to return samples to base. All these applications can benefit from wireless sensors. For instance, Infrared sensors can be used alongside visible light cameras for object detection and classification and assisting the robotics arms to maneuver accurately. Humidity and temperature sensors can be used during ground drilling, while vibration sensors can monitor the drill operation. Navigation without GPS on planetary surfaces requires dedicated active wireless links with precise time of arrival measurements (e.g. one example is the Ultra wide band radios developed at JSC). Other techniques such as passive RFID tags and readers may also be used to find asset in know areas pre-marked with tags.

## Challenges:

- Capability to operate and survive dust or radiation storm
- Mobile chemical and biological sensor units
- Long range reliable link back to base with navigation capabilities

## Benefits:

- In situ testing of samples
- Navigation without need for GPS
- Dynamic control of robotic arms using wireless sensors and actuators



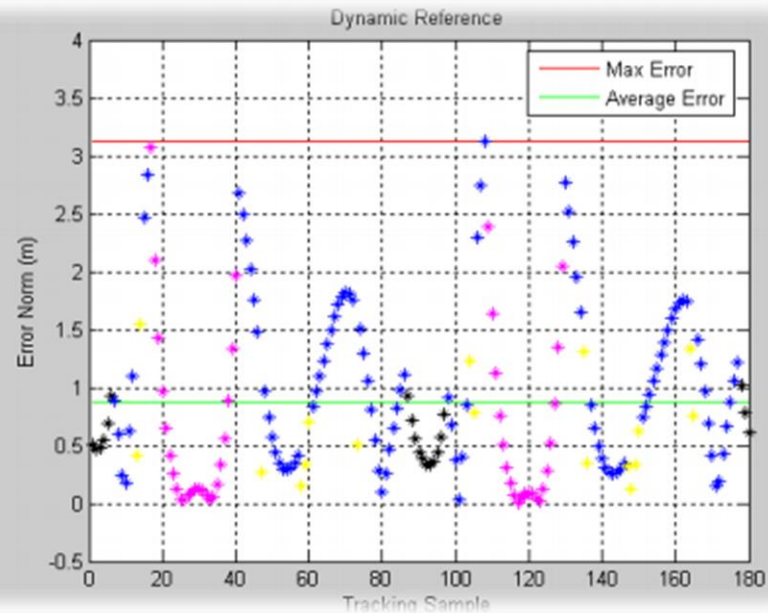
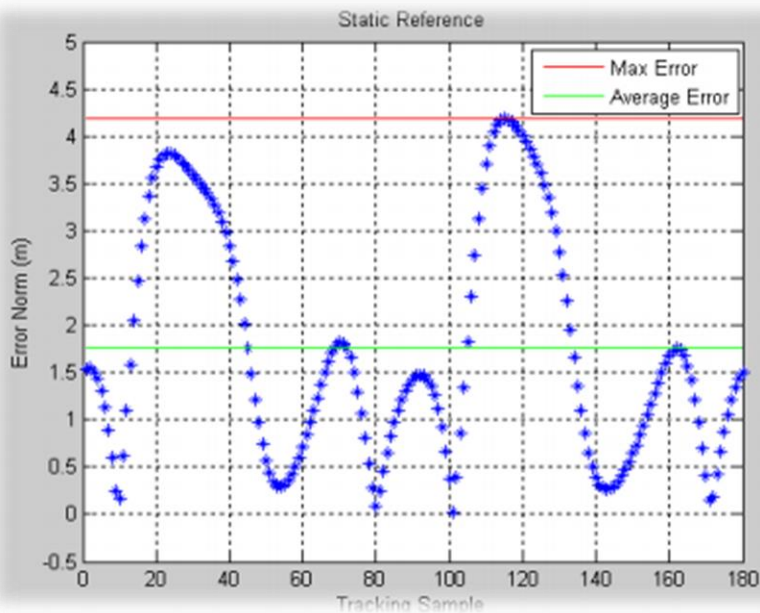
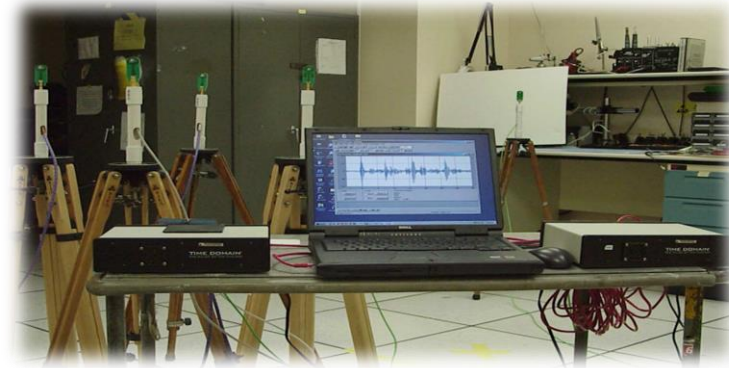
NASA's SEV



# Example: JSC's UWB Tracking System

**Resolution: 0.8762m (dynamic), 1.7660m (Static)**

**Barton, et. al.,** IEEE/ACES Int'l Conference on Wireless Communications and Applied Computational Electromagnetics, 2005.





# Ground systems

Ground testing often requires structural sensors such as strain gauges, accelerometers, and deflection sensors. Testing fuel tanks may require leak detection sensors, hydrogen or other gas sensors, humidity, and temperature sensors. Performance tests are conducted in controlled environment with thermal cycles that mimic space conditions. Therefore, all these instrumentation, although used on earth, need to be capable of operating in harsh environments. Wiring and cabling may be cumbersome, costly, or may be infeasible in some cases. Therefore, wireless sensing in ground system can open up lots of new opportunities to gather critical data.

## Challenges:

- High precision in sampling and data transfer
- Interference management among large number of sensors sending data
- Working within limitations of test setup at specific distances

## Benefits:

- Acquiring more data for structural analysis that is possible using wires
- Reducing cost of tests due to cable elimination
- Flexibility of test for adding more sensors later without redesigning the whole wiring plan
- Versatility in programming test beds for future tests



MSFC Structural testing laboratory





# Examples: Slides 34-36



Structural test



SIL/DBOB



# Habitats

Autonomous monitoring of habitats, living conditions, and inventory tracking are the main use case scenarios that can benefit from wireless technology. RFID based inventory tracking methods for autonomous logistical management (ALM) is being developed at JSC and can tie into the habitat monitoring itself. Integrating sensors as load on RFID devices and reading the changes in the response in addition to ID numbers is a promising approach in this direction. Monitoring living conditions including physical (temperature, humidity, and radiation), chemical (air and water quality) and biological (mold and mildew or other airborne bacteria) are some critical applications that require wireless sensors. Another important aspect of monitoring habitat systems is evaluating cognitive changes of its inhabitants, i.e. crew health monitoring. Real time vital signs tracking and wireless sensors for sleep behavior monitoring are essential for ensuring mission success. For more info on habitat systems refer to section 3.6 in this report.

## Challenges:

- Wide range of temperature and radiation variations
- Aggregation challenges in multi model sensor data with different sampling rates and precisions
- Signal propagation in metallic enclosures

## Benefits:

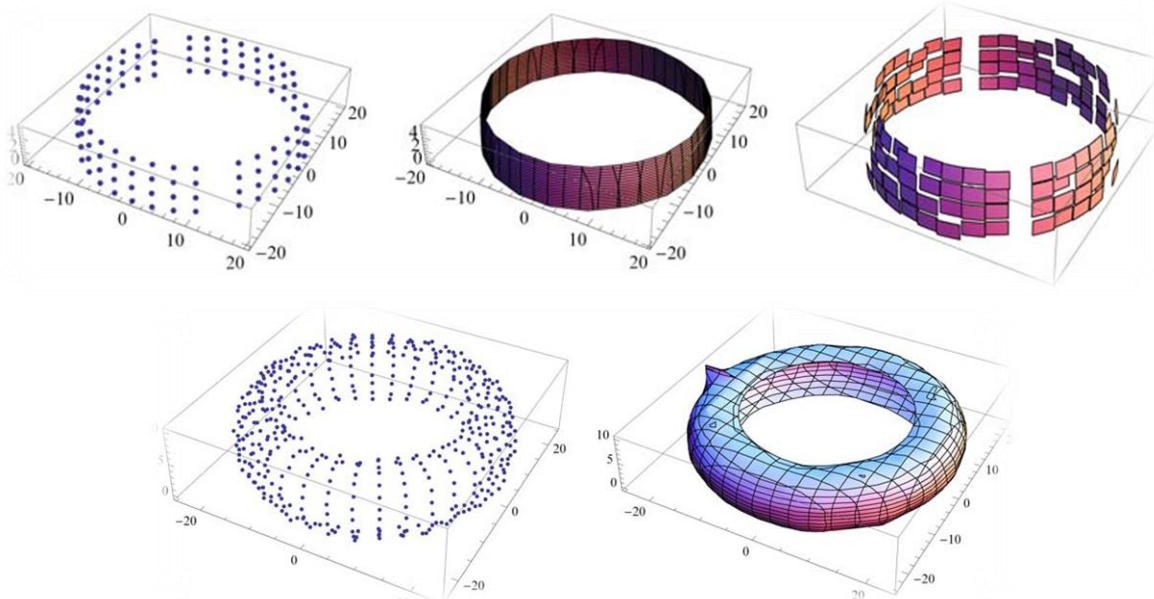
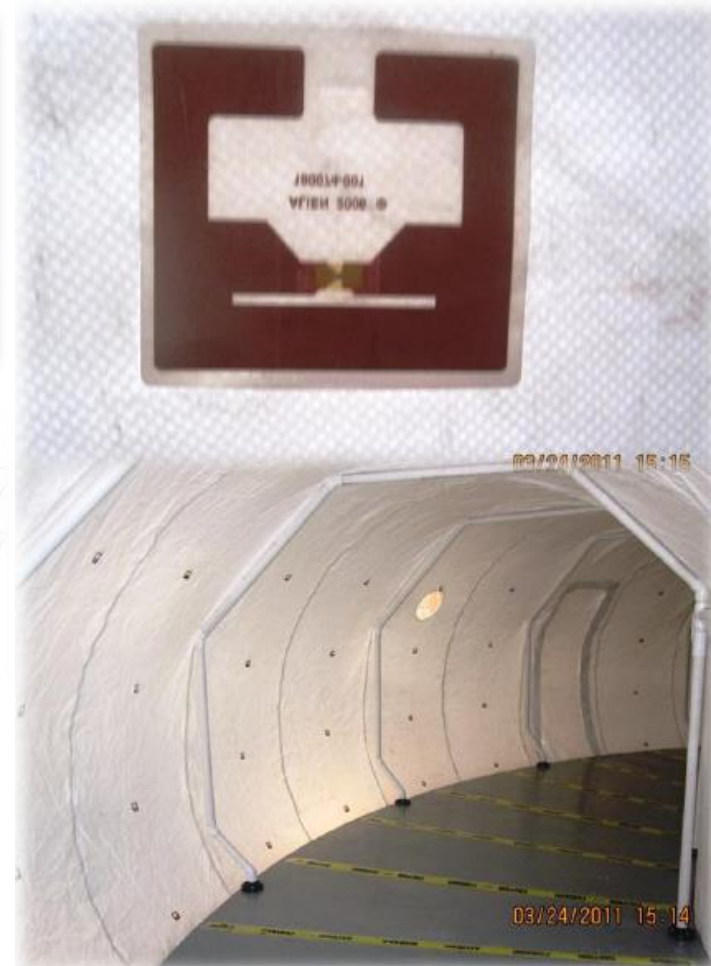
- Acquiring more data from habitat structure
- Reducing weight due to cable elimination
- Flexibility of change in design and sensor location after the deployment



MSFC Habitat



# Example: Inflatable Space Habitat



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# Application specific requirements\*

- TA2.4: Engine health monitoring;
- TA3.3: Wireless power transmission;
- TA5.2: Radio Frequency (RF) Communications;
- TA5.5: Cognitive networks;
- TA6.4: Environmental monitoring and sensors;
- TA7.4: Habitat systems;
- TA10.4: Sensors and actuators

\* [References \[13-16\]](#)

\* [References \[17-18\]](#)

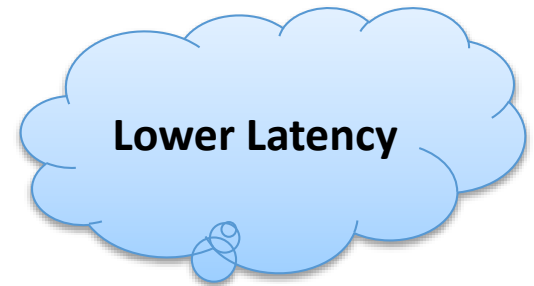
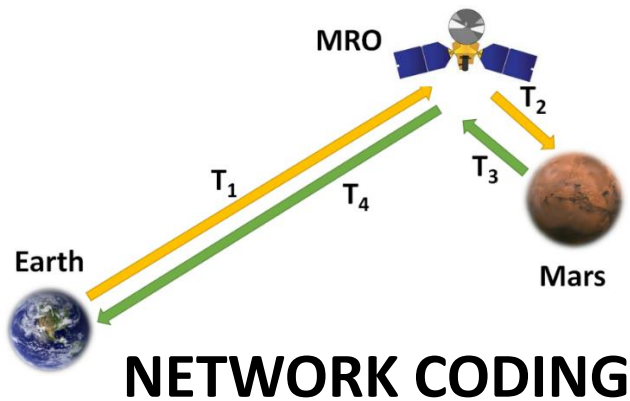
\* [References \[19\]](#)

\* NASA Technology Roadmap [1]

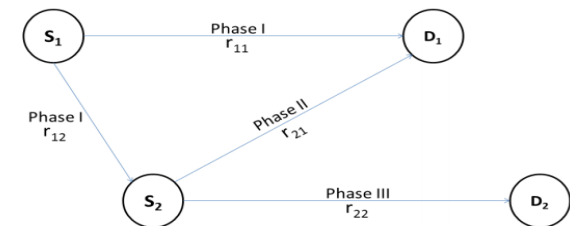
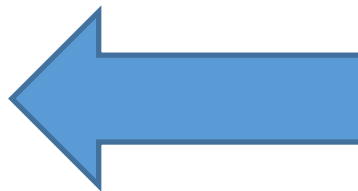




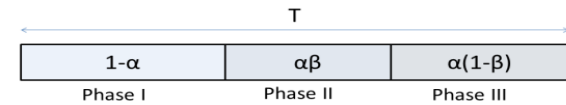
# TA 5.2 and TA 5.5



## COGNITIVE NETWORKS



(a) Network Model



(b) Time Frame Model



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# Potential technology areas

Use case \ Technology area	TA2.4 Engine Health	TA3.3 Wireless Power	TA5.2 RF Comm	TA5.5 Cognitive Networks	TA6.4 Environmental Monitoring	TA7.4 Habitat Systems	TA10.4 Sensors & Actuators
2.1. Space vehicles							
2.2. Satellites and payloads							
2.3. Surface explorations							
2.4. Ground systems							
2.5. Habitats							

- Dark shaded squares indicate closely related technical areas and application use cases
- lightly shaded cells indicate potential benefit from wireless technology broadly defined



# Roadmap for wireless technology development

Where we are	Short term <5 Yr	Long term, 5-10 Yr	Where we want to go
1. Not space certified, rad tolerant or rad hard		X	1. Space certified
2. Low reliability		X	2. High reliability
3. Limited# of networked nodes	X		3. Large network sizes
4. Not scalable	X		4. Scalable
5. Not reconfigurable		X	5. Reconfigurable
6. Lack of coexistence in transmit protocols		X	6. Coexisting protocols with cognition
7. Battery dependent	X		7. Battery free

## Concluding Remarks:

- Wireless Technology has the potential to be used in space applications
- It offers unique capabilities that are not obtainable in wired systems
- The space application areas are varied and each have a unique set of requirements
- Rapid development in wireless industry can be used as stepping stone



# Future technologies – 5G and beyond

- 1G (AMPS), 2G (GSM/CDMA), 3G (e.g. UMTS, HSPA and 1X-EV-DO), 4G (LTE, LTE-A), 5G (?)

- Massive MIMO
- **RAN** Transmission cm and mm Waves
- New Waveforms
- Shared Spectrum Access
- Advanced Inter-Node Coordination
- Simultaneous Transmission Reception
- Multi-**RAT** Integration & Management
- **D2D** Communications
- Efficient Small Data Transmission
- Wireless Backhaul/Access
- Integration
- Flexible Networks
- Flexible Mobility
- Context Aware Networking
- Information Centric Networking
- Moving Networks

**RAN:** Radio Access Networks

**RAT:** Radio Access Technology

**D2D:** Device to Device





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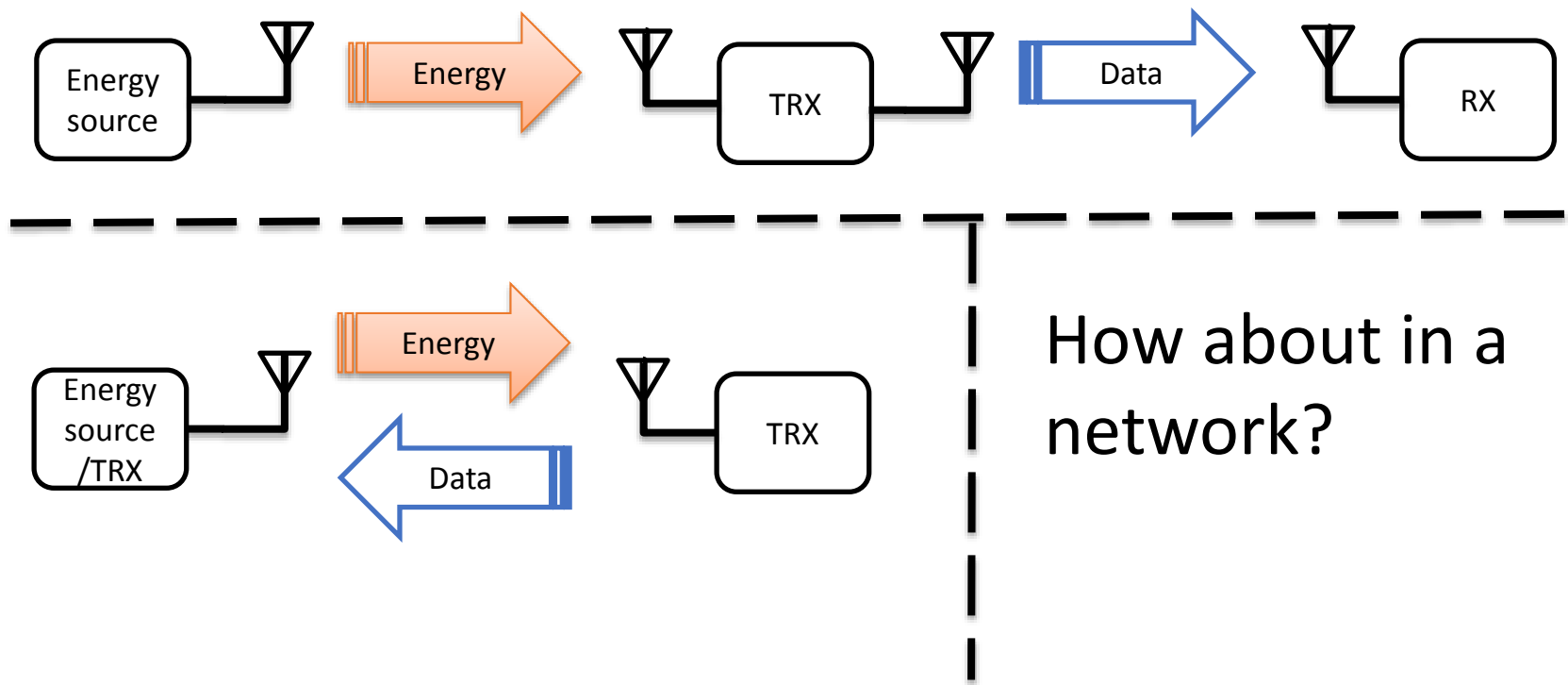


# Some examples

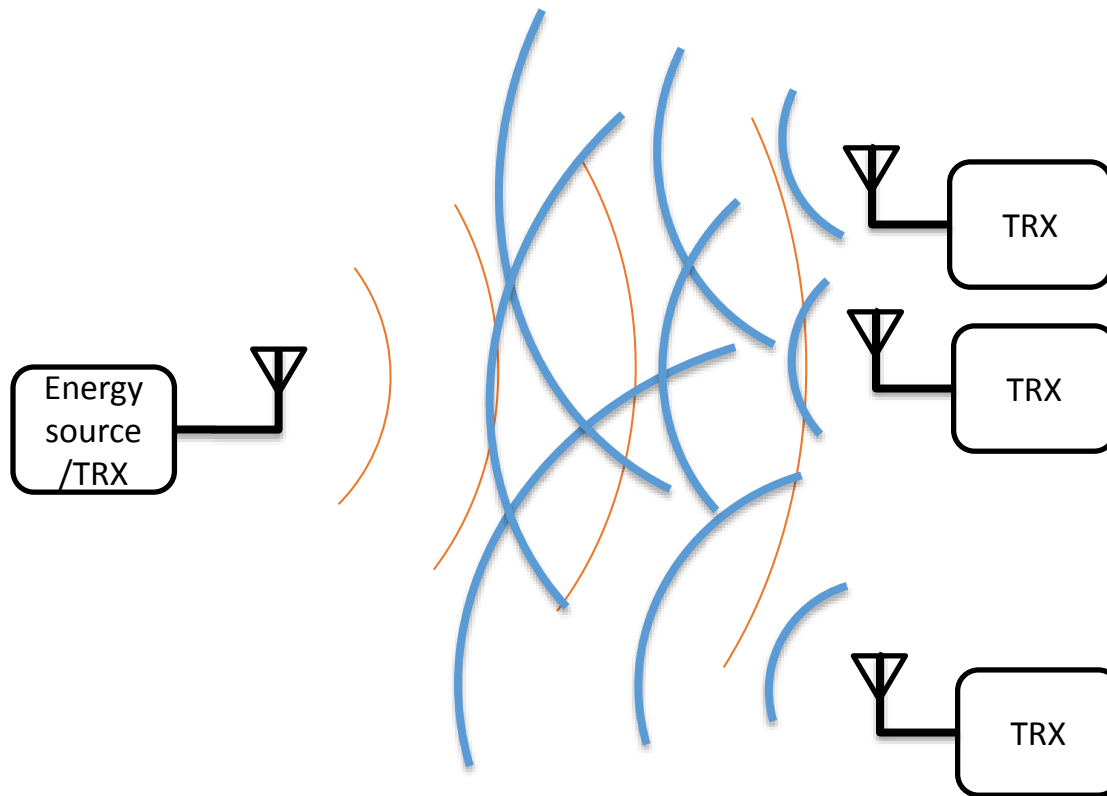
1. Wireless power transfer
2. Structural tests data analysis
3. Wireless Deflection Sensor
4. DBOBs/SIL



# Energy Wireless ~~Power~~ Transfer (WPT)



# Wireless Network



## What are the challenges?

- Interference
- Energy scheduling
- Data scheduling
- Energy beam forming
- Data beam forming
- Parallel or joint?



# Smart Wireless Energy Transfer (SWET)

What is the best way to transfer energy wirelessly?

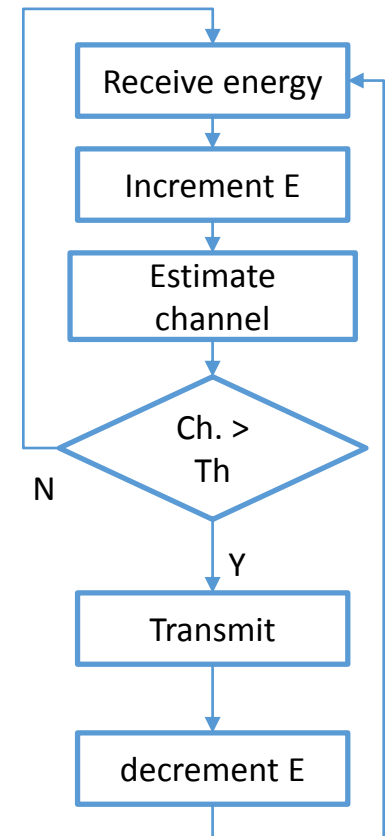
- a) Send energy periodically, transmit data periodically ☒
- b) Send energy periodically, transmit data randomly ☒
- c) Send energy randomly, transmit data periodically ☒
- d) Send energy randomly, transmit data randomly ☒





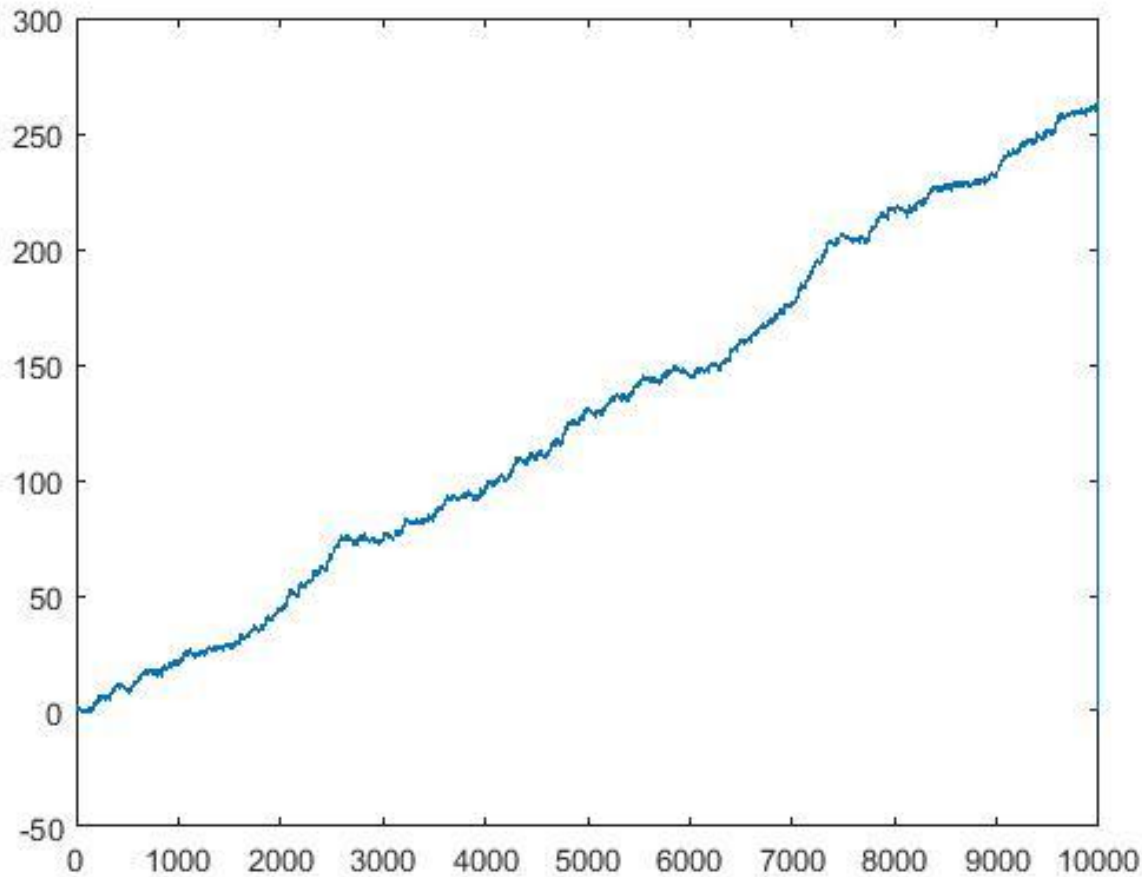
# Transmit When Risk is Low (TWRL)

- Let us assume  $\text{Transmit Energy} = 1.1 * \text{Received Energy Pulse}$
- Consider an Additive White Gaussian Noise (AWGN) channel model
- Transmit energy at every time slot for 10,000 pulses
- Transmit data whenever the AWGN channel condition is better than a pre-specified threshold
- Normalizing all equations, the critical threshold is  $\sim 1.6$
- Run simulations and determine outage whenever the remaining battery charge is 0 or negative.



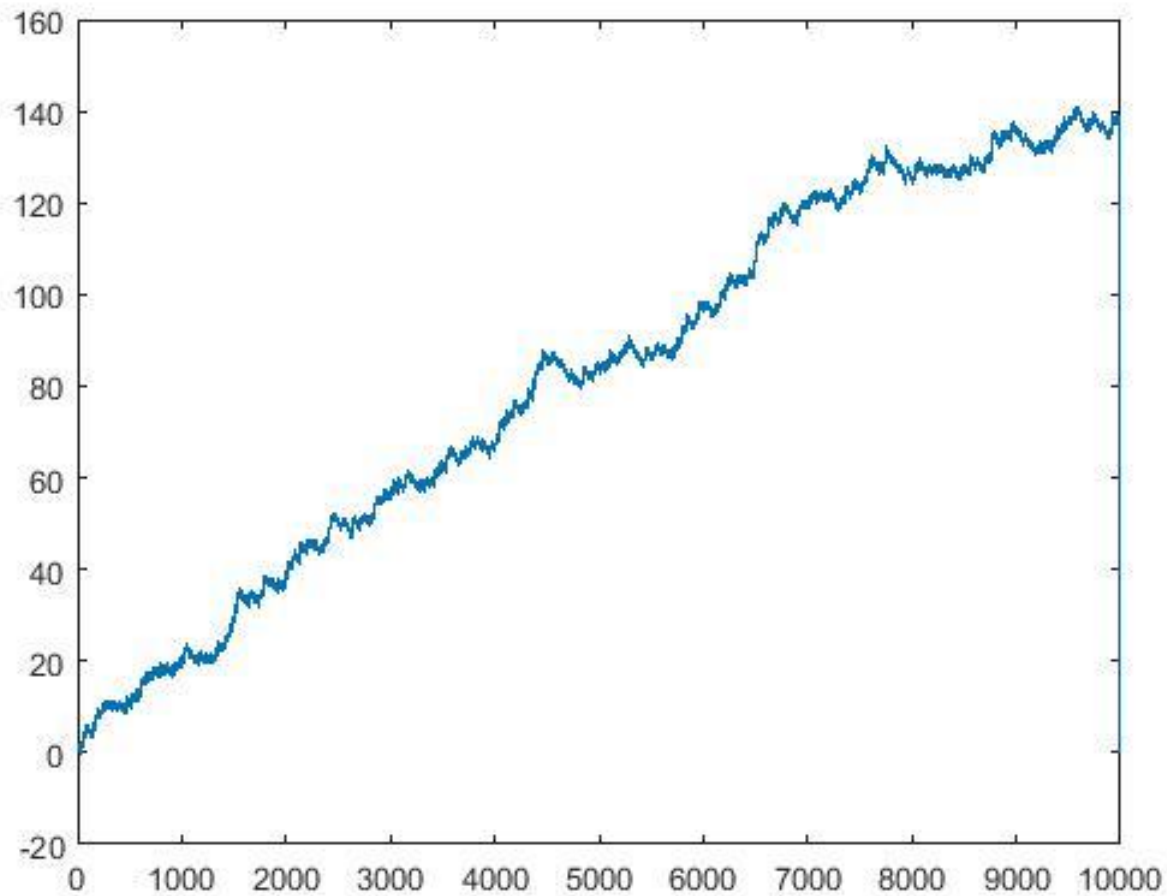
Threshold = 1.5

Outage =  $10e-5$



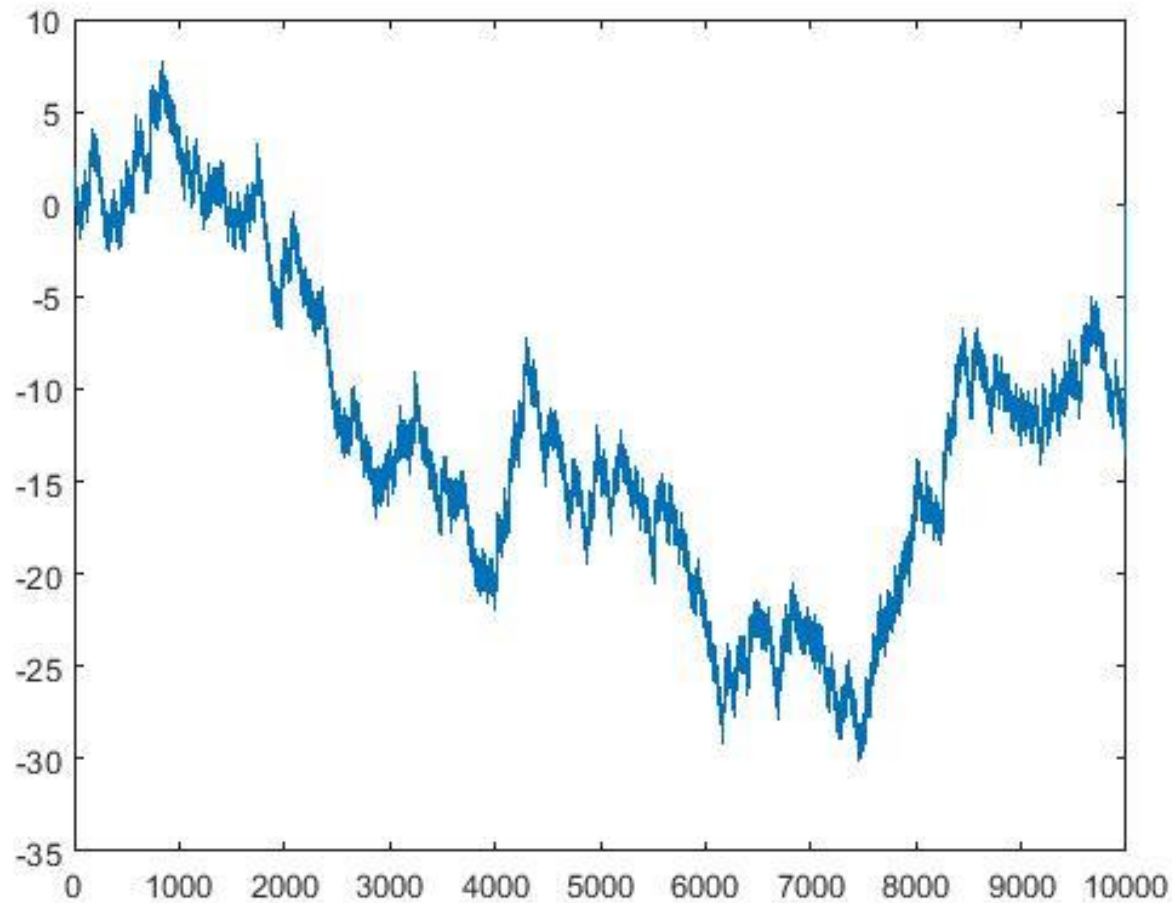
Threshold = 1.6

Outage =  $10e-4$



Threshold = 1.7

Outage = 90%



# How about fading channels?

- Repeat this experiment for Rayleigh or Rician Fading channels
- How about the case that energy transfer is also stochastic?
- What if we add a reserve battery to be used when energy is low? How that can be designed to reduce outage to a desired level?
- What role will interference play in transmission scheduling?



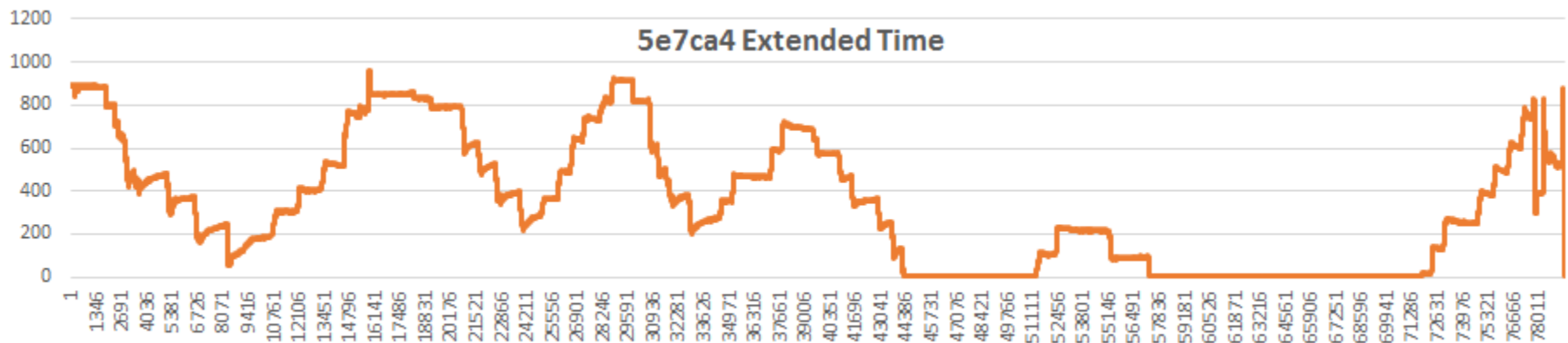
# Structural Test Data Analysis

July 25, 2016 Strain Sensor  
Test with Synapse radios

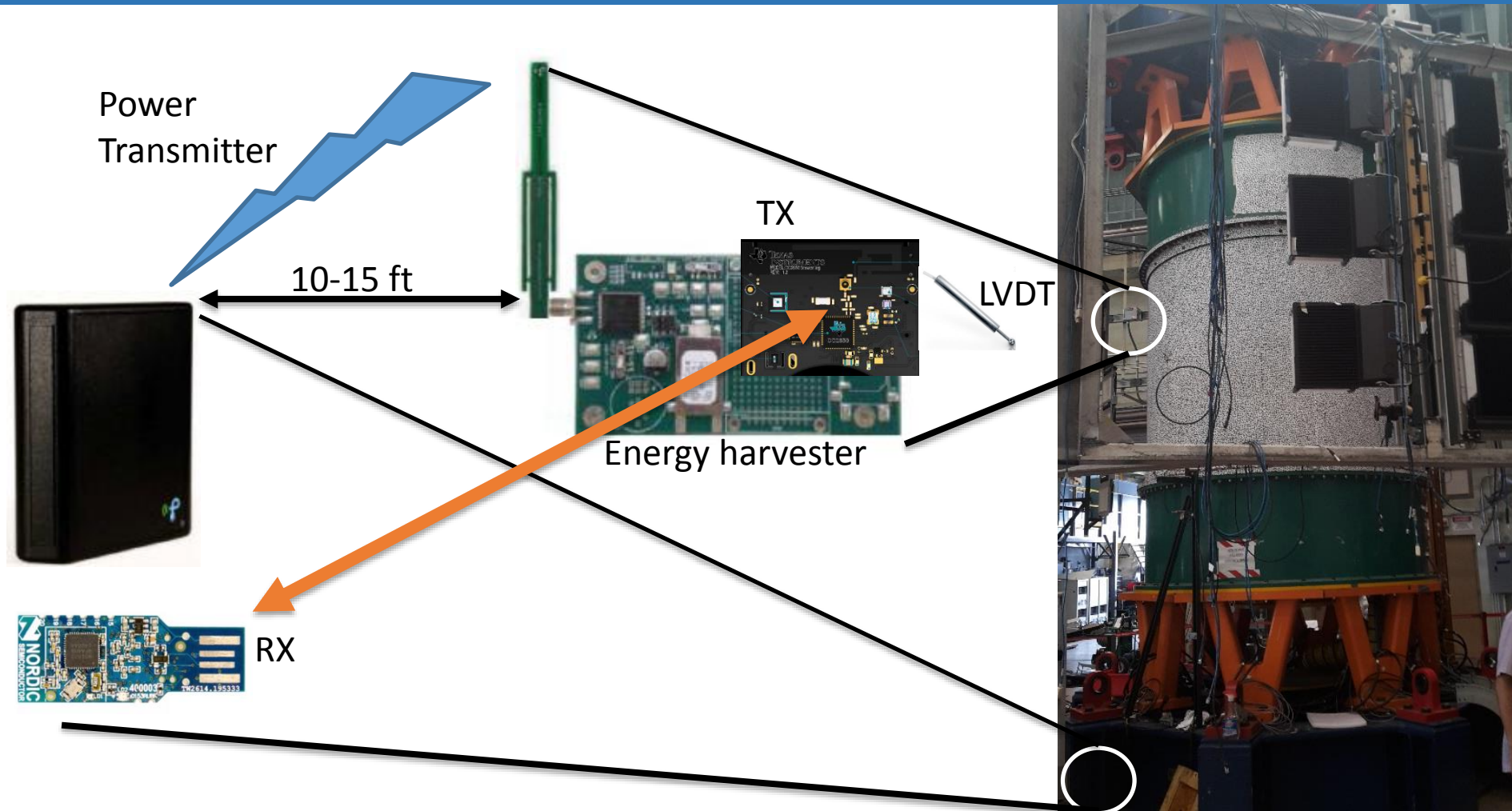
Node ID	No of Packets
5e7b00	26175packets
<b>5e7ca4</b>	<b>79348packets</b>
5e7a5a	24553packets
5e7cc5	26585packets
5e7a47	24692packets

## Lessons learned:

- Metal plate under sensors → Add Insulator
- Strong WiFi interference → add shielding
- Sensor data anomaly → calibrate
- Interference among nodes → one at a time
- Issues with analog front end → new boards



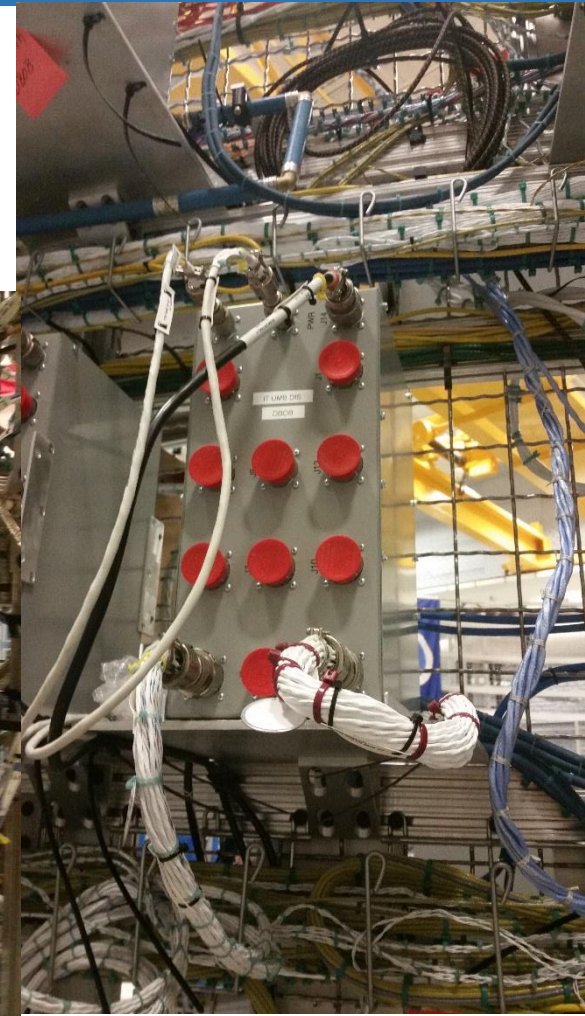
# Wireless Deflection Sensors





# DBOBs/SIL

- There are 23 DBOBs on each half cylinder at SIL
- Each RS422 connector has 8 ports with 10 MHz bandwidth
- Each one communicates with multiple devices analog/digital
- Signals range from 4mv to 40v DC



# Acknowledgments

- Thanks to NASA MSFC Faculty Fellows program managers and their staff members for funding this research project.
- Thanks to engineers and scientists at NASA MSFC ES36 group who shared their thoughts and ideas on using wireless sensing technologies in space applications.
- Special thanks to Branch Chief, DeLisa Wilkerson, for guiding this research, coordinating tours, visits, and interviews, and great suggestions.

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**UMAINE.EDU/WISENETLAB**



# IEEE Int'l Conference on Wireless for Space and Extreme Environments (WiSEE)

**WiSEE 2013**  
Baltimore, MD  
GSFC / UMD

**WiSEE 2014**  
Amsterdam, NL  
ESA / ESTEC

**WiSEE 2015**  
Orlando, FL  
KSC/ UCF

**WiSEE 2016**  
Aachen, Germany  
DLR / U of Aachen

**WiSEE 2017**  
Montreal, QC  
CSA / Concordia

**WiSEE 2018**  
TBD  
NASA / ?

**WiSEE 2019**  
Ottawa, ON  
CSA / U of Ottawa

**WiSEE 2020**  
TBD  
ESA / ?

**WiSEE**  
2016

